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14. ABSTRACT

Magnetic resonance imaging techniques were used to investigate the 3D mean flow and turbulent mixing around a film cooled turbine vane. The overall objective was to understand the turbulent mixing in a complex flow and develop tools to determine the non uniform temperature distribution incident on a downstream turbine rotor. Magnetic resonance velocimetry provided the three component velocity distribution throughout a double passage vane cascade. The magnetic resonance concentration technique was used to measure the concentration of film

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Report Title

Final Report: Turbulent Dispersion of Film Coolant and Hot Streaks in a Turbine Vane Cascade

ABSTRACT

Magnetic resonance imaging techniques were used to investigate the 3D mean flow and turbulent mixing around a film cooled turbine vane. The overall objective was to understand the turbulent mixing in a complex flow and develop tools to determine the non uniform temperature distribution incident on a downstream turbine rotor. Magnetic resonance velocimetry provided the three component velocity distribution throughout a double passage vane cascade. The magnetic resonance concentration technique was used to measure the concentration of film coolant injected from trailing edge slots. The turbulent dispersion was strongly affected by vortex structures produced by film cooling slots. The passage vortex increased the spread of coolant near the end walls. Combustor hot streaks injected upstream of the cascade dispersed very slowly because turbulence is strongly suppressed by the acceleration through the cascade. A separate experiment examined the relevance of magnetic resonance experiments in water to turbine flows at high subsonic Mach numbers in air. Identical 3D mixing layer experiments were performed with low speed water mixing a chemical agent and high speed air flows mixing temperature. The dimensionless concentration/temperature profiles were nearly identical between the experiments.

Enter List of papers submitted or published that acknowledge ARO support from the start of the project to the date of this printing. List the papers, including journal references, in the following categories:

(a) Papers published in peer-reviewed journals (N/A for none)

Received		Paper
01/07/2015	4.00	Sayuri D. Yapa, John L. D'Atri, John M. Schoech, Christopher J. Elkins, John K. Eaton. Comparison of magnetic resonance concentration measurements in water to temperature measurements in compressible air flows, Experiments in Fluids, (10 2014): 0. doi: 10.1007/s00348-014-1834-1

TOTAL: 1

Number of Papers published in peer-reviewed journals:

(b) Papers published in non-peer-reviewed journals (N/A for none)

Received	Paper

TOTAL:

Number of Papers published in non peer-reviewed journals:

(c) Presentations

Number of Presentations: 0.00

Non Peer-Reviewed Conference Proceeding publications (other than abstracts):

Received	Paper

TOTAL:

Number of Non Peer-Reviewed Conference Proceeding publications (other than abstracts):

Peer-Reviewed Conference Proceeding publications (other than abstracts):

Received		Paper
01/07/2015	5.00	Christopher Elkins, John Eaton, Sayuri Yapa. Quantitative MRI Measurements of Hot Streak Development in a Turbine Vane Cascade, ASME Turbo Expo 2015: Turbine Technical Conference and Exposition. 15-JUN-15, . : ,
01/18/2015	8.00	Sayuri Yapa, Christopher Elkins, John Eaton. Endwall vortex effects on turbulent dispersion of film coolant in a turbine vane cascade, ASME Turbo Expo 2014. 16-JUN-14, . : ,
01/18/2015	9.00	Sayuri Yapa, Christopher Elkins, John Eaton. Quantitative mri measurements of hot streak development in a turbine vane cascade, ASME Turbo Expo 2015. 15-JUN-15, . : ,

TOTAL: **3**

Number of Peer-Reviewed Conference Proceeding publications (other than abstracts):

(d) Manuscripts

Received		Paper
11/04/2013	1.00	Sayuri Yapa, Christopher Elkins, John Eaton. Endwall Vortex Effects on Turbulent Dispersion of Film Coolant in a Turbine Vane Cascade, ASME 2014 International Gas Turbine Institute (10 2013)

TOTAL: **1**

Number of Manuscripts:

Books

Received Book

TOTAL:

Received Book Chapter

TOTAL:

Patents Submitted

Patents Awarded

Awards

Graduate Students

NAME	PERCENT_SUPPORTED	Discipline
Sayuri D. Yapa	0.33	
John D'Atri	0.00	
FTE Equivalent:	**0.33**	
Total Number:	**2**	

Names of Post Doctorates

NAME	PERCENT_SUPPORTED
	0.00
New Entry	0.00
FTE Equivalent:	**0.00**
Total Number:	**1**

Names of Faculty Supported

NAME	PERCENT_SUPPORTED	National Academy Member
John K. Eaton	0.05	
FTE Equivalent:	**0.05**	
Total Number:	**1**	

Names of Under Graduate students supported

NAME	PERCENT_SUPPORTED	Discipline
John Schoech	0.00	Mechanical Engineering
John D'Atri	0.00	Mechanical Engineering
FTE Equivalent:	**0.00**	
Total Number:	**2**	

Student Metrics

This section only applies to graduating undergraduates supported by this agreement in this reporting period

The number of undergraduates funded by this agreement who graduated during this period: 2.00

The number of undergraduates funded by this agreement who graduated during this period with a degree in science, mathematics, engineering, or technology fields:...... 2.00

The number of undergraduates funded by your agreement who graduated during this period and will continue to pursue a graduate or Ph.D. degree in science, mathematics, engineering, or technology fields:...... 2.00

Number of graduating undergraduates who achieved a 3.5 GPA to 4.0 (4.0 max scale):...... 2.00

Number of graduating undergraduates funded by a DoD funded Center of Excellence grant for Education, Research and Engineering:...... 0.00

The number of undergraduates funded by your agreement who graduated during this period and intend to work for the Department of Defense 0.00

The number of undergraduates funded by your agreement who graduated during this period and will receive scholarships or fellowships for further studies in science, mathematics, engineering or technology fields:...... 0.00

Names of Personnel receiving masters degrees

NAME	
John D'Atri	
Total Number:	**1**

Names of personnel receiving PHDs

NAME	
Sayuri Yapa	
Total Number:	**1**

Names of other research staff

NAME	PERCENT_SUPPORTED
Christopher Elkins	0.10
FTE Equivalent:	**0.10**
Total Number:	**1**

Sub Contractors (DD882)

Inventions (DD882)

Scientific Progress

See Attachment

Technology Transfer

We have been talking routinely with engineers at GE Aircraft Engines, GE Research, Honeywell Aero Engines, and ANSYS about our results. we have transferred data sets and solicited their comments on the relevance of our work.

Final Progress Report

Turbulent Dispersion of Film Coolant and Hot Streaks in a Turbine Vane Cascade

Agreement Number: W911NF-11-1-0506

John K. Eaton, Christopher J. Elkins, Sayuri D. Yapa
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Stanford, CA 94305
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Overview

High pressure turbine blades in gas turbine engines are exposed to extremely harsh environments, so the first stage turbine is often the component that limits both engine performance and life. The blades are exposed to high mean temperatures and large spatial temperature variations, which cause high thermal stresses and low-cycle fatigue failure. The temperature variations are caused by non-uniformities exiting the combustor and incomplete mixing of film coolant from the upstream nozzle vane. If the temperature distribution at the turbine inlet was known accurately, the blade cooling system could be designed to minimize the blade metal temperature non-uniformities, thereby minimizing both coolant use and thermal stresses. The problem is that existing CFD codes cannot accurately predict the temperature distribution. One of the main reasons for this is the inadequacy of the turbulent mixing models, which generally grossly overpredict the mixing rate.

The focus of this research program was to provide highly detailed data showing how coolant and hot streaks are mixed as they pass through a nozzle vane row and in the nozzle row wake upstream of the turbine. The key was to acquire well-resolved, three-dimensional, full-field data around a film cooled turbine vane cascade using recently developed measurement techniques based on magnetic resonance (MR) imaging. Such full field turbulent mixing data are unprecendented in any highly complex flow, and in particular in turbine vane cascades. The full-field data was then used to understand what the critical flow mechansisms were responsible for temperature dispersion. Furthemore, the full-field data sets are ideal for validating computational techniques.

Magnetic resonance based measurements of three-dimensional velocity and scalar concentration fields in turbulent flows was pioneered by our research group prior to the present research program. However, the present application is more complex than any previously studied using these techniques. Therefore, a secondary goal of the research was to extend the capabilities to more complex flow configurations and to prove that the results are applicable to real gas turbines. The latter goal led to the development of a second experimental configuration that was not in the original proposal. This experiment was accessible to both MR measurements and conventional probe techniques allowing direct comparison.

Several different experiments were performed over the course of this program. The overall goal was to pioneer new methods for studying turbulent mixing in complex flows and to apply those techniques to the study of critical mixing phenomena related to gas turbine cooling. Measurements of coolant dispersion in a double-passage turbine vane cascade serve as the primary experiment. A second experiment was designed to investigate the dispersion of combustor hot streaks in a high pressure turbine vane cascade. Lastly, an experiment which proves the validity of using concentration measurements in an incompressible fluid to thermal behavior in a compressible flow environment was performed. This experiment uses a three-dimensional mixing layer to validate the use of magnetic resonance velocimetry (MRV) and MRC in water flows to represent compressible gas flows. Progress in each of these three areas is summarized below.

Double-Passage Cascade Experiments

The main experiment is a double-passage cascade representing the flow around a typical turbine nozzle vane in an infinite cascade of such vanes. This apparatus was designed using a CFD-based optimization scheme using an open-literature vane shape. A modern pressure-side cutback film cooling configuration was added to the vane trailing edge. The experimental program started with 3D velocity measurements through the entire apparatus using Magnetic Resonance Velocimetry (MRV). These measurements confirm that the velocity field in the experimental test section was comparable to the results from the CFD simulations that were used to determine the wall shapes for the double-passage vane cascade. The results from this MRV also showed that the vane's suction-side boundary layer transitioned from laminar to turbulent about two-thirds of the chord length downstream of the leading edge. A 2 mm-tall boundary layer trip was added at the suction peak to ensure a fully turbulent boundary layer. A second MRV was performed to get more detailed velocity data in the wake of the trailing edge at a higher resolution than could be performed for the full-field. Additionally, multiple calibration scans were performed to determine how to properly acquire Magnetic Resonance Concentration (MRC) data. This process is used to determine the relationship between signal magnitude from a processed MRC data set and the concentration of copper sulfate solution (the working fluid) , and is vital in investigating mixing using MRC.

Two sets of MRC experiments were performed: low concentration and high concentration. The low concentration experiment uses a 0.015M copper sulfate solution as the coolant fluid. The main flow uses deaerated water as its working fluid, and the MRC technique measures the concentration of the copper sulfate as it mixes with the main flow. This concentration of copper sulfate was used because a linear calibration curve between signal magnitude and copper sulfate concentration exists for up to a concentration of 0.015M. The high concentration data set uses a 0.08M copper sulfate solution as the coolant fluid. The purpose of this second set of data was to get accurate, quantitative measurements of the mixing behavior in the far-wake of the airfoil. In the low concentration data, the signal magnitude is too weak to provide accurate analysis in the far-wake region.

Figure 1 which plots a 2% isosurface of coolant concentration provides an overview of the mixing processes near the trailing edge. The coolant streak from each slot is bulged toward the pressure side of the vane by vortex structures formed behind each slot. The streaks remain coherent downstream of the vane indicating that they will cause significant spatial variation in the leading edge temperature of the downstream blade. Another interesting feature that can be observed is that the streaks decay more quickly near the endwalls. Figures 2 and 3 make this quantitative. Figure 2 plots the concentration profile c(n) at various streamwise locations. Here n is the coordinate normal to the vane trailing edge chord line. These profiles are averaged over the central span of the vane. They indicate that the coolant is diffusing slowly in the wake and the spread is faster in the positive n direction. This latter observation is caused by the same vortices developed around the trailing edge cutback. Figure 3 shows profiles measured across the span near the central peak of the mean concentration profiles. It is interesting that the spanwise variability initially increases then begins to fall due to the effects of turbulent mixing. The initial increase in spanwise variation is caused by the effects of the longitudinal vortices. The slow turbulent dispersion apparently is caused by reduction in freestream turbulence as the flow accelerates through the cascade.

Figure 1. Two percent isosurface of coolant concentration downstream of the trailing edge breakout.

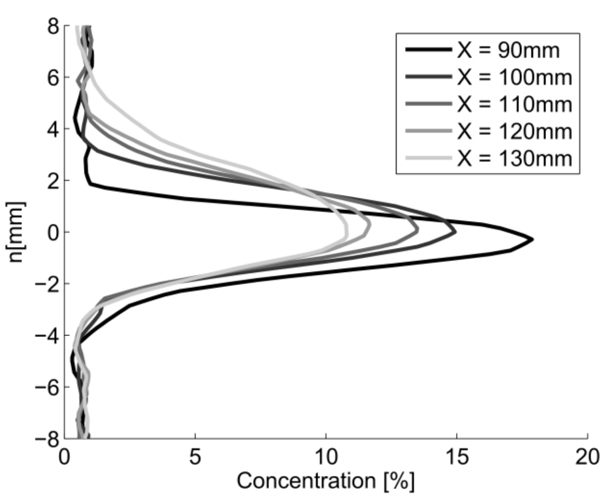


Figure 2. Coolant concentration profiles averaged over the central part of the vane span.

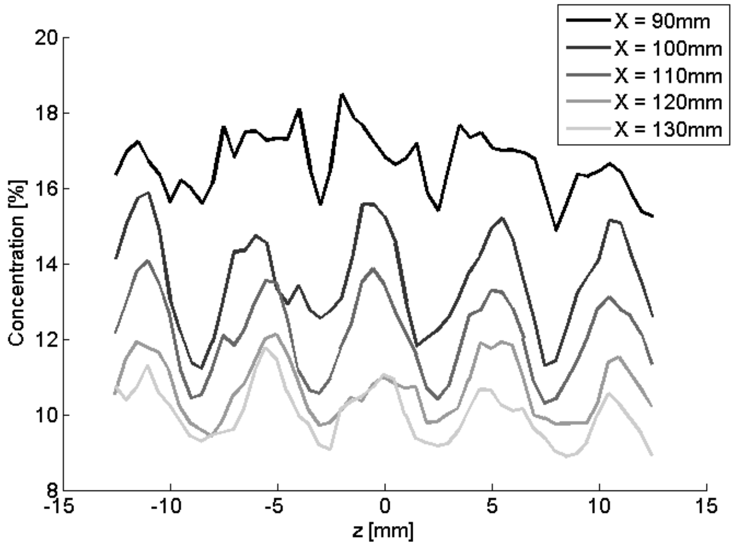


Figure 3. Coolant concentration profiles across the span at various streamwise positions.

The full-field measurements also allowed examination of vortex structures near the vane endwalls, in particular the dominant passage vortex. Figure 4 shows two rakes of streamlines that start just above the stagnation line in the two endwall regions. These streamlines were computed from the measured three component velocity field. They show that the passage vortex undergoes at least 180 degrees of rotation along the length of the passage. The passage vortex on each endwall has a very major effect on dispersion of coolant streaks emitted near the each end of the airfoil.

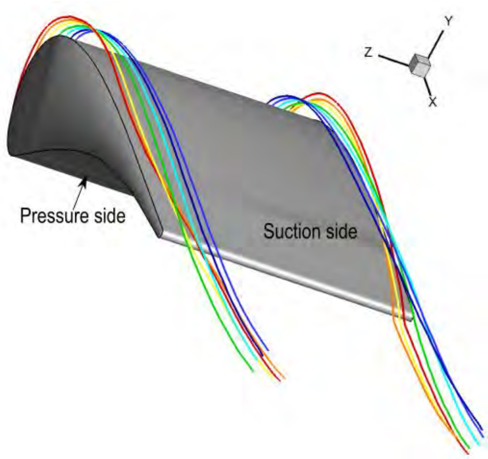
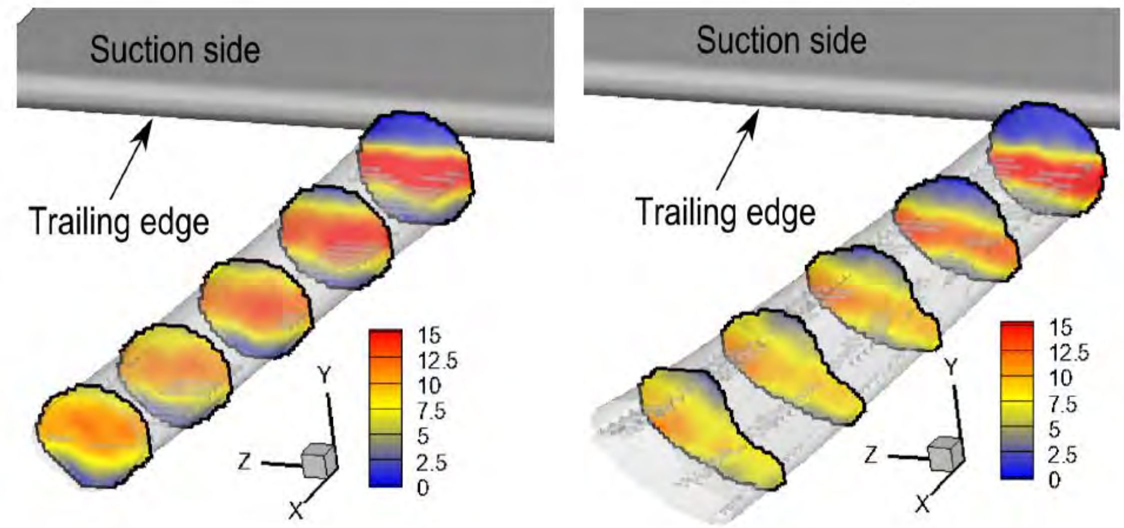


Figure 4. Streamlines from the measured velocity field indicating the presence and strength of a passage vortex on each endwall.

The passage vortices have a major effect on dispersion of coolant streaks emitted near the each end of the airfoil. The first evidence of this is Figure 1, where the coolant streaks on each end dissipate earlier than in the central region. Figure 5 shows additional evidence. In this figure, two streamtubes are plotted, again calculated from the measured velocity field. One streamtube is near the endwall, and the other is in the center span of the airfoil. The concentration distribution inside the streamtube is plotted on five planes for each case. Near the center span, the streamtube remains circular but reduces in diameter going downstream due to streamwise acceleration in the wake. However, near the end wall, the streamtube is highly distorted by the presence of the passage vortex. The perimeter of the streamtube grows rapidly due to this distortion, and the concentration falls more quickly.



(a) Streamtube seeded with center at $z = 0$ mm

(b) Streamtube seeded with center at $z = -22$ mm

Figure 5. Streamtubes downstream of vane trailing edge at the center span and near the endwall. Each streamtube was calculated by computing a set of streamlines starting at various points along a circle. The streamlines were calculated using the measured three-dimensional velocity field.

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This work was reported in an archival paper: (Yapa, S.D., Elkins, C.J., and J.K. Eaton "Endwall Vortex Effects on Turbulent Dispersion of Film Coolant in a Turbine Vane Cascade", Proc. ASME Turbo Expo 2014, Dusseldorf, Germany, GT2014-25484.) Chapter 4 of Sayuri Yapa's thesis, (attached to this report) also covers this topic.

Hot Streaks Generator Experiments

The behavior of hot streaks originating in the combustor and their impact on turbine vanes and blades was investigated using a simplified geometry with discrete streaks injected in the inlet of a double passage vane cascade. The test geometry was the same pressure-side cutback cooled high pressure turbine vane. Three hot streaks were released upstream of the vane on the spanwise centerline and aligned to pass over the suction-side, center, and pressure-side of the vane. Streamtubes and concentration isosurfaces and contours were calculated from the three-dimensional experimental data, and it was found that the streamtubes experience significant distortion from their original circular cross-sections as they travel through the test section. Concentration isosurfaces (plotted in Figure 6) experience similar distortion effects, and the peak concentration in a streamtube decreases by as much as 90% (in the suction side hot streak). The pressure side hot streak experiences the smallest drop in peak concentration, while the peak concentration in the center hot streak diminishes somewhat more than this due to its interaction with the pressure side cutback cooling. However, it is important to note that coherent hot streaks still exist at the exit of the test section, and that non-uniform concentration conditions exist at all streamwise locations in the test section. This suggests that turbulence suppression by strong acceleration plays a significant role in maintaining the streaks. The concluding message from these experiments is that the temperature distribution of the gases impacting the blades downstream of the turbine vanes remains significantly non-uniform.

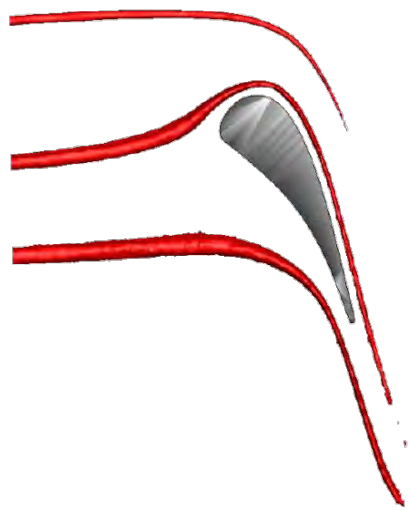

Figure 6. Normalized concentration isosurfaces of the three hot streaks. The concentration plotted in these hot streaks have been normalized with respect to the concentration value at the inlet to the test section (far left of the figure).

The hot streaks experiments were informative, but have much room for future improvements. As in the endwall vortex study, size remains a constraint in the double passage vane cascade experiments. The large degree of turning in this cascade and the size limitations present in the MRI setup restrict the maximum size of the vane to be studied. Given that the one dimensional side length of a voxel is around 0.5mm, an injection diameter of 3 mm-diameter hot streaks gives a starting injection diameter only 6 voxels across at its maximum width. In the future, a new experimental setup that has larger hot streaks and/or a larger vane size would be very beneficial to extracting extra information from this experiment. Additionally, the interaction of the hot streak with the passage vortex might yield very interesting results that can be used to further inform turbine designers. This experiment could be performed readily as the current hot streak generator setup can be used to explore the behavior of hot streaks located at various spanwise positions.

The power of the MRC/MRC technique lies in both its ease in acquiring three-dimensional fields as well the ability to acquire data without disturbing the flow in the vane wake. Optical techniques are difficult to apply in this configuration due to the large amounts of turning in the test section geometry and measurement techniques such as hot wire anemometry or temperature probe experiments would physically disturb the flow being measured. The MRV/MRC technique is able to provide full information about both the velocity field and the scalar mixing occurring in the test section. The hot streaks work is detailed in a new paper that has been accepted for presentation at the ASME-IGTI meeting in June 2015, Yapa, S.D., Elkins, C.J., and J.K. Eaton "Quantitative MRI Measurements of Hot Streak Development in a Turbine Vane Cascade", Proc. ASME Turbo Expo 2015, Montreal, Canada, GT2015-42767.) It is also covered in Chapter 5 of Sayuri Yapa's thesis attached to this document.

Investigation into the Effect of Compressibility on MRV Analysis of Gas Turbine Engines

Magnetic resonance imaging (MRI) measurements in liquid flows provide highly detailed 3D mean velocity and concentration data in complex turbulent mixing flow applications. The scalar transport analogy is applied to infer the mean temperature distribution in high speed gas flows directly from the MRI concentration measurements in liquid. Furthermore, the measured surface concentration is used to infer the adiabatic film cooling effectiveness over an entire surface. An advantage of the concentration measurements is that the adiabatic condition can be realized exactly, something that is very difficult in thermal tests. Compressibility effects on turbulent mixing are known to be weak for simple flows at high subsonic Mach number, and it was not known if this would hold in more complex flows characteristic of practical applications. Furthermore, the MRI measurements are often done at lower Reynolds number than the compressible application, although both are generally done in fully turbulent flows.

Our working hypothesis was that MRI measurements performed in water are transferable to high subsonic Mach number applications providing that the Reynolds number of the experiments is high enough to be fully turbulent. The present experiment was designed to compare stagnation temperature measurements in high speed airflow ($M = 0.7$) to concentration measurements in an identical water flow apparatus. The flow configuration was a low aspect ratio wall jet with a thick splitter plate producing a 3D complex downstream flow mixing the wall-jet fluid with the mainstream flow. The three-dimensional velocity field is documented using magnetic resonance velocimetry in the water experiment, and the mixing is quantified by measuring the mean concentration distribution of wall-jet fluid marked with dissolved copper sulfate. The airflow experiments are operated with a temperature difference between the main stream and the wall jet. Profiles of the stagnation temperature are measured with a shielded thermocouple probe. The flow configuration was specifically designed to minimize any effects of thermal conduction on the temperature measurement.

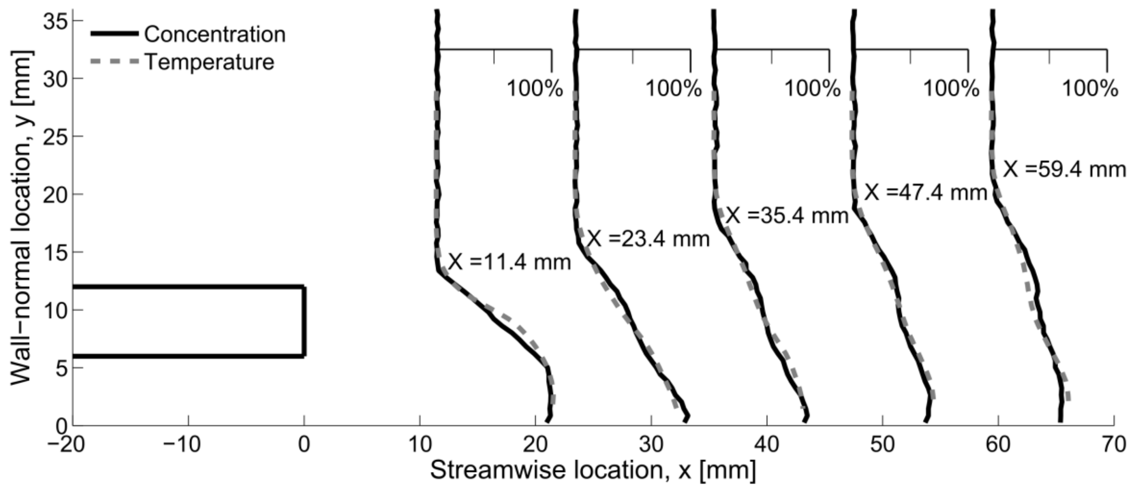

Fig 7. Comparison between concentration from water experiments and corrected temperature profiles from high subsonic Mach number air experiments.

Figure 7 shows the results measured on the centerline of the channel. The results show excellent agreement between normalized temperature and concentration profiles after correction of the temperature measurements for the effects of energy separation. The agreement is within 1 % near the edges of the mixing layer, which suggests that the mixing characteristics of the large scale turbulence structures are the same in the two flows. We believe that this experiment proves that MRI techniques applied in water flows can be used to quantitatively measure adiabatic temperature distributions and adiabatic film cooling effectiveness for flows at high subsonic Mach number. The MRI techniques acquire velocity and temperature (concentration) data over the full 3D field, making the results invaluable for development of new models. Often thermal experiments only acquire surface values or profiles at a few discrete locations.

This work is described in detail in a recently published paper Experiments in Fluids, Yapa et al. (2014).

Personnel Involved

All of the work has been supervised by Professor John Eaton. Dr. Sayuri Yapa completed her Ph.D. in January 2015. She worked on the double-passage cascade experiments, hot streaks generator experiments, andco-supervised the compressibility effects experiment. Dr. Chris Elkins, a Senior Research Engineer at Stanford is developing new MRI experimental techniques as well as exploring new methods for extracting the turbulent diffusivity. One undergraduate student, John D'Atri, worked on the compressibility effects experiments. Mr. D'Atri was a senior and concentrated his efforts on the temperature measurements half of the compressibility effects experiments. One MS student Matthew Hoffman participated in setting up the air flow experiment, and another undergraduate, John Schoech built the water-flow version of the same experiment All of the students completed their degrees during the grant period.

Publications

Yapa, S.D., Elkins, C.J., and Eaton, J.K. "Endwall Vortex Effects on Turbulent Dispersion of Film Coolant in a Turbine Vane Cascade", Proc. ASME Turbo Expo 2014, Dusseldorf, Germany, GT2014-25484.

Yapa, S.D., D'Atri, J.L., Schoech, J.M., Elkins, C.J., and Eaton, J.K. (2014) "Comparison of Magnetic Resonance Concentration Measurements in Water to Temperature Measurements in Compressible Air Flows," *Experiments in Fluids*, 55, 1834.

Yapa, S.D., Elkins, C.J., and J.K. Eaton "Quantitative MRI Measurements of Hot Streak Development in a Turbine Vane Cascade", Proc. ASME Turbo Expo 2015, Montreal, Canada, GT2015-42767.

Yapa, S.D. *Turbulent Coolant Dispersion in the Wake of a Turbine Vane Trailing Edge*, Ph.D. Dissertation, Mechanical Engineering Dept., Stanford University, Jan. 2015.